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The Parameters Controlling the Burning Efficiency of *In-Situ* Burning of Crude Oil on Water

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Abstract

Parameters that control the burning efficiency of *in-situ* burning of crude oil on water were identified by studying the influence of the initial slick thickness, vaporization order, oil slick diameter, weathering state of the oil, heat losses to the water layer and heat flux to the fuel surface on the burning efficiency for light and heavy crude oils. These parameters were studied in several small scale and intermediate scale experimental setups. The results showed that the heat losses to the water layer increase with increasing burning time because the components in a crude oil evaporate from volatile to non-volatile. Due to the relatively low heat feedback (re-radiation and convection, in kW/m^2) to the fuel surface of small scale pool fires, as compared to large scale pool fires, these heat losses were shown to limit the burning efficiency in small scale experiments. By subjecting small scale crude oil pool fires to an incident heat flux, the burning efficiency of a light crude oil could be increased from 48% to 90%. Similarly, increasing the diameter from 0.1 to 1.1 m, which thus increased the heat feedback to the fuel surface, increased the burning efficiency from 41% to 84% for a light crude oil. It can be concluded that the pool fire diameter is the key parameter that determines the burning efficiency of crude oil fires on water, which was partially attributed to the increasing heat flux (in kW/m^2) to the fuel surface with increasing diameter. Increasing the heat flux to the fuel surface through external radiation resulted in an increase of the burning efficiency in small scales experiments. The burning efficiencies were, however, still lower than the ≥ 90% burning efficiencies observed in large scale fires of crude oil on water. It is therefore probable that other factors also increase the burning efficiency as the burning diameter increases.

1 Introduction

One of the main marine oil spill response methods that is currently being considered in the Arctic is *in-situ* burning of the oil (Buist et al., 2013; EPPR, 2015). This response method features the ignition and subsequent burning of a spilled oil slick, leading to the removal of the oil from the water surface by turning the liquid oil into soot and gaseous combustion products. The effectiveness of this response method is most commonly expressed in terms of the burning efficiency, here defined as the amount of oil (in wt%) that is removed from the water surface during the burning. It has been shown through test operations and field experiments that *in-situ* burning has the potential to remove 90-99% of the spilled oil (Allen, 1990; Bech et al., 1993; Fingas et al., 1994; Potter, 2010). These high burning efficiencies are one of the reasons stated for the potential of *in-situ* burning as marine oil spill response method in Arctic waters (e.g. Buist et al. (2013)).

Much lower burning efficiencies, however, as low as 32%, have also been observed in experimental studies, both for similar and different experimental conditions (Bech et al., 1993; Farmahini Farahani et al., 2015b; Fritt-Rasmussen et al., 2012). In order for *in-situ* burning to be a successful oil spill response method, it is important that such low burning efficiencies can be avoided. Due to the widely varying experimental conditions (oil type and weathering state, experimental scale, environmental conditions, etc.) among these *in-situ* burning tests, however, it is currently unclear by which experimental parameters the burning efficiency is mainly controlled. Without a solid understanding of these parameters, it is not possible to make accurate predictions on the effectiveness of *in-situ* burning as response method for a given oil spill scenario. Such uncertainties could limit the applicability of *in-situ* burning as response method when low burning efficiencies need to be taken into account in the decision-making process of a response to an oil spill (see e.g. Fritt-Rasmussen et al. (2013)). It is therefore important to identify the parameters that control the burning efficiency of *in-situ* burning of crude oil on water.

In this study, the parameters that control the burning efficiency of *in-situ* burning of crude oil on water were identified by studying the influence of the initial slick thickness, vaporization order, oil slick diameter, weathering state of the oil, heat losses to the water layer and heat flux to the fuel surface on the burning efficiency for light and heavy crude oils. Although these parameters are not the only parameters that could affect the burning efficiency of crude oil burning on water, they were found to be suitable for the purpose of this study. The selected parameters were studied in several small and intermediate scale experimental setups that allowed for studying each parameter in a systematic approach. The results from each individual parameter were then compared to the other parameters to determine the parameters that had the largest influence on the burning efficiency.

2 Methodology

The data used in this study consisted of a compilation of data previously published on the initial slick thickness, the vaporization order, heat losses to the water layer, weathering state of the oil and the heat flux to the fuel surface, which was supplemented with new experimental data from small scale experiments with additional oil types and a series of experiments in ice cavities with various diameters. The influence of the initial slick thickness (Van Gelderen et al., 2015), the vaporization order (Van Gelderen et al., 2017a) and heat losses to the water layer (Van Gelderen et al., 2017a) on the burning efficiency were studied in the Crude Oil Flammability Apparatus (COFA). This experimental setup features a 1.0 x 1.0 x 0.5 m^3 water basin with a Pyrex glass cylinder on an open foot to contain the oil on the water (Figure 1). The open foot allowed water to flow into the bottom of the cylinder to compensate for the regressing surface of a burning oil and thus maintain the level of the oil surface constant for a longer period of time. Initial slick thicknesses of 2-40 mm were used to study the effect of the initial slick thickness. The vaporization order and heat losses to the water layer were studied by monitoring the flame height, mass loss rate (see Van Gelderen et al. (2017a)) and the temperature distribution in the oil and water layer as a function of the burning time.

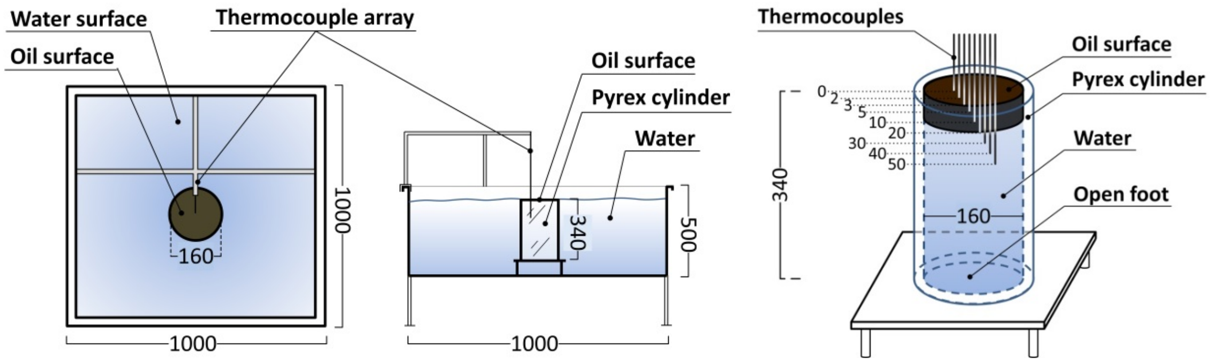

Figure 1. Schematics of the COFA setup from a top view (left) and cross sectional view (middle) and a close-up of the Pyrex glass cylinder on its open foot featuring the thermocouple distribution in the oil layer (right). All measurements are in mm. Adapted from Van Gelderen et al. (2015).

The influence of the weathering state of crude oil and the heat flux to the fuel surface were studied under a cone calorimeter (Van Gelderen et al., 2017b), featuring a custom made, circular stainless steel cone holder (Figure 2). Rather than being directly cooled by an underlying water layer, the oils in this setup were cooled by a continuous flow (7 L/h) of cold water (12 °C). The water flow and temperature were calibrated so that the burning rate and burning efficiency for a light crude oil (DUC, see Table 1) in the cone setup without an external heat flux matched the results for the same oil in the COFA. Oils tested in this setup were subjected to incident heat fluxes ($\dot{q}''_{inc}$) of 0, 5, 7, 8, 10, 20, 30, 40 and 50 kW/m^2 to determine the effect of the heat flux to the fuel surface on the burning efficiency. The oils tested in this setup included a fresh light, heavy and refined fuel oil and weathered light oils with 30 and 40 wt% evaporative losses (DUC 30/0 and DUC 40/0) and 40 wt% evaporative losses emulsified with 40 vol% water content (DUC 40/40) (see Table 1 below).

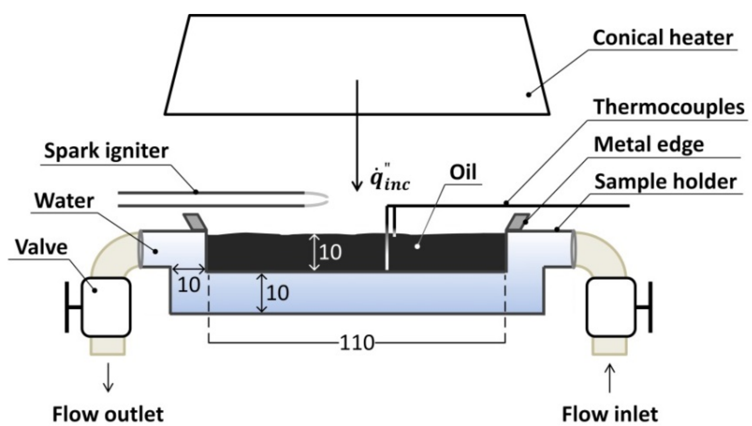

Figure 2. Schematic of the custom made cone calorimeter setup. All measurements are in mm. Adapted from Van Gelderen et al. (2017b).

The influence of the pool diameter was studied among three ice cavities sizes with diameters of 0.1 and 0.25 m and a 1.0 x 1.0 m^2 square area (effective diameter of 1.1 m) (Figure 3). The initial oil slick thickness in these experiments was 10 mm. In the smallest ice cavities, the ullage height, initial water layer and initial oil slick thickness were also studied as a function of the burning efficiency to be able to exclude the influence of these parameters on the burning efficiency among the different scales (see Van Gelderen (2017)). More information and additional data on these ice cavity experiments has been reported by Farmahini Farahani et al. (2015a), Farmahini Farahani et al. (2015b) (smallest cavity size) and Shi et al. (2016) (largest cavity size).

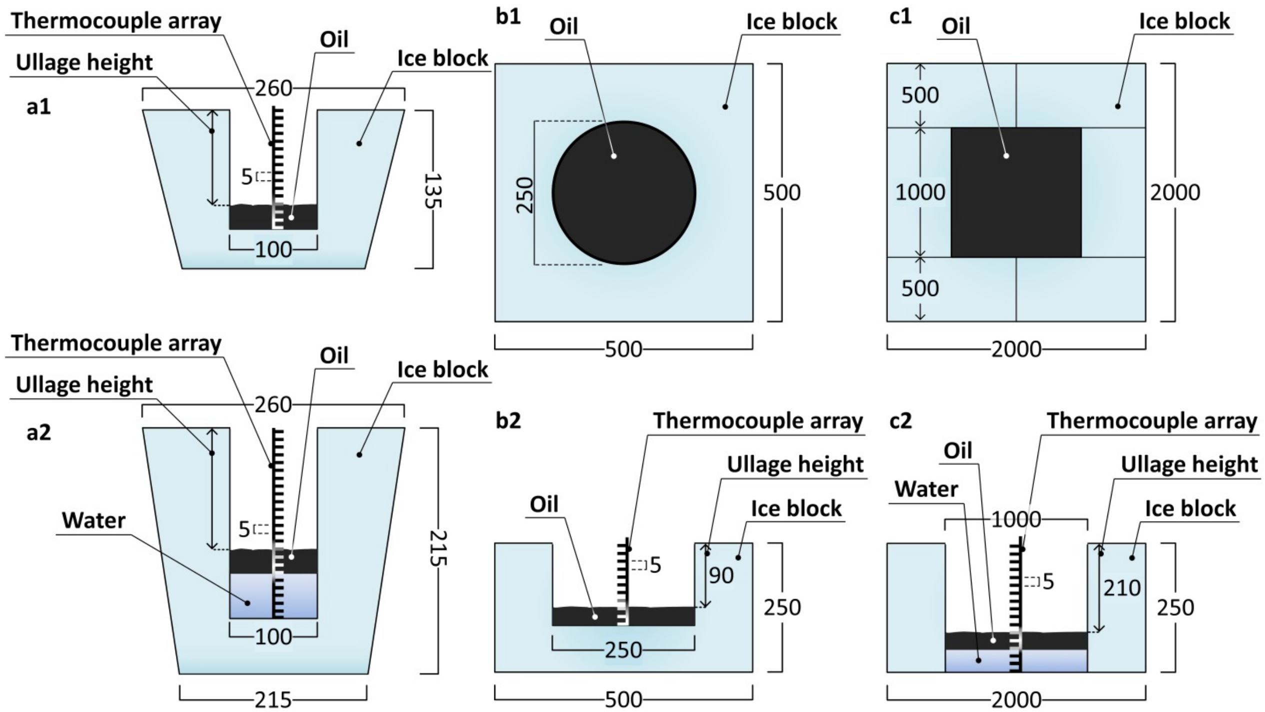

Figure 3. Schematics of the small (a), medium (b) and large (c) ice cavity setups. Higher ice blocks (a2) were used in the small ice cavity experiments to test deep ullages (100 mm) and initial water layers. Schematics of the medium and large ice cavities show a top view (b1 and c1) and cross sectional view (b2 and c2). All measurements are in mm.

Table 1 shows the oils that were used in each of the experimental setups, including some of the physical and chemical characteristics for each oil. Of the used oils, only DUC 30/0, DUC 40/0 and DUC 40/40 were weathered oils. A specific methodology for each of the discussed experimental setups is beyond the scope of this study and can be found in the aforementioned references. Here, a general methodology is described that was applicable for all experimental setups. A known amount of uniformly mixed oil (in kg), corresponding to an initial slick thickness of 2-40 mm, was added carefully to the area containing the oil. The oil was then ignited with a butane hand torch, or in case of experiments with an incident heat flux ≥ 5 kW/m^2 with the spark igniter, and the oil was let to burn until it extinguished naturally. The residue mass was determined either by collecting the residue with 3M hydrophobic absorption pads and weighing the residue (COFA and largest ice cavity setups) or by weighing the mass of the setup with and without the residue (cone and small and medium ice cavity setups). The burning efficiency was then calculated with Eq. (1)

$$Burning\ efficiency = \frac{mass_{initial} - \ mass_{residue}}{mass_{initial}} \cdot 100\% \tag{1}$$

Table 1. Physical and chemical characteristics of the used (crude) oils

Oil	*Density (g/ml)*[a]	*Boiling point (°C)*	*Flashpoint (°C)*[b]	*Viscosity (cP)*[a]	*Wax/asphaltenic content (wt%)*	*Setup*
n-Octane (C_8H_{18})	0.699	125-126	13	0.386	-	COFA
Dodecane ($C_{12}H_{26}$)	0.745	215-217	71	1.294	-	COFA
Hexadecane ($C_{16}H_{34}$)	0.770	287	135	3.036	-	COFA
Gasoline[c]	0.74-0.78	30-260	< -40	NA	-	COFA
Diesel	0.823	150-385[d]	65-66	3.350	-	COFA
DUC	0.853	230+	7	6.750	4.2/< 0.05[e]	COFA/Cone
DUC 30/0	0.897	NA	80	44.93	NA	Cone
DUC 40/0	0.900	NA	102	60.91	NA	Cone
DUC 40/40	0.924	NA	NA	93.20	NA	Cone
REBCO	0.863	300+	23	12.40	4.9/1.0[f]	COFA
ANS	0.871	NA	21	10.85	3.0/1.8[h]	Ice cavities
Grane	0.934	380+	20-21	268.7	7.0/0.9[g]	COFA/Cone
IFO 180	0.968	330+	90	969.3	NA/NA	COFA/Cone

[a] Measured at 25 °C using an Anton Paar SVM 3000 viscometer.
[b] Measured using a Pensky-Martens Flash Point Tester: PM 4 (closed cup).
[c] Shell (2011); [d] BP (2011); [e] Maersk Oil (2005); [f] DG environment (2009); [h] BP (2015); [g] Statoil (2017), different values have been reported in Fritt-Rasmussen et al. (2012).

3 Results and Discussion

3.1 Vaporization Order and Heat Losses

Figure 4 shows the burning efficiencies of all the different oil types tested in the COFA setup at initial slick thicknesses of 5 and 10 mm, apart from the alkane mixture (15 mm) and hexadecane (20 mm). The alkane mixture was a 1:1:1 volumetric ratio mixture of octane, dodecane and hexadecane. The results clearly show that the burning efficiency decreases with a decreasing amount of volatile components and an increasing amount of non-volatile components in the oils (seen from the flashpoint and density, Table 1). Herein, volatile components can be related to the components in the light fraction of a crude oil (boiling point < 204 °C) and non-volatile components to the medium and heavy fractions of a crude oil (boiling point ≥ 204 °C) (Buist et al., 1997). This trend is caused by a combination of the vaporization order of the crude oils, i.e. the order in which its components evaporate during combustion, and the increase of instantaneous heat losses to the water layer during the burning. Other parameters, such as the initial temperatures of the water and the oil slick, which varied between 5-25 °C, were not found to significantly affect the burning efficiency results.

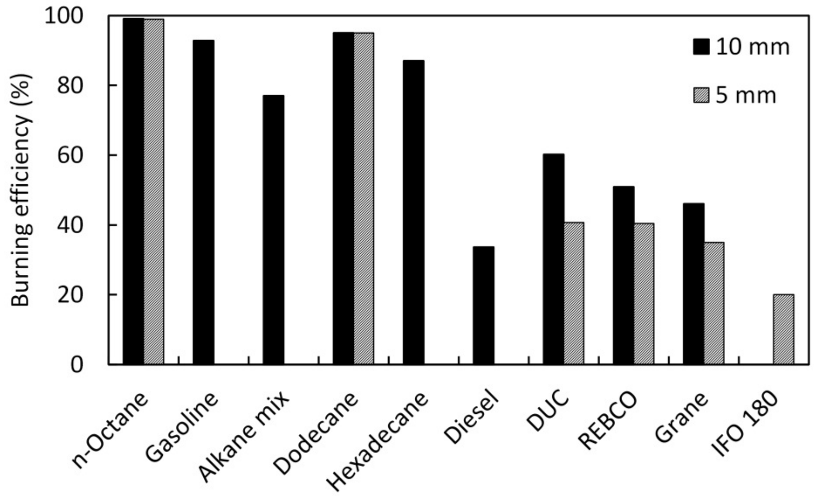

Figure 4. Burning efficiency as a function of the oil type for oils burned in the COFA. The oils are ordered from left to right by increasing density. Burning efficiencies of the alkane mixture (1:1:1 volumetric ratio mixture of octane, dodecane and hexadecane) and hexadecane were obtained for an initial slick thickness of 15 and 20 mm, respectively.

It was shown in Van Gelderen et al. (2017a) that the vaporization of multicomponent fuels is volatility controlled, in order of decreasing volatility. This was, among others, evident from a decreasing flame height as a function of the burning time and a depletion of the light components in the burn residue (Figure 5). The consequence of this vaporization order is that as the burning progresses, a crude oil requires more energy to vaporize the less volatile components. The burning rate and flame height decrease, however, for less volatile components, resulting in less heat being fed back to the fuel surface to evaporate the non-volatile components. In addition, the boiling point of non-volatile components is higher than of volatile components, which causes the burning crude oil surface to heat up over time. Because the water below the oil effectively acts as an infinite heat sink, the oil at the oil-water interface heats up much slower than the burning surface as it loses heat to the water. The initial heat losses therefore cause the temperature gradient in the oil slick to increase over time for crude oils (Figure 6), which subsequently leads to higher heat losses over time. Thus, as a crude oil burns, more energy per second is needed to evaporate the heavier components, while less energy per second is supplied to the surface from the flame and more energy per second is lost to the water layer. These three effects ultimately cause the fire to extinguish prematurely, as the evaporation rate becomes too low to sustain the fire, and thus negatively affect the burning efficiency.

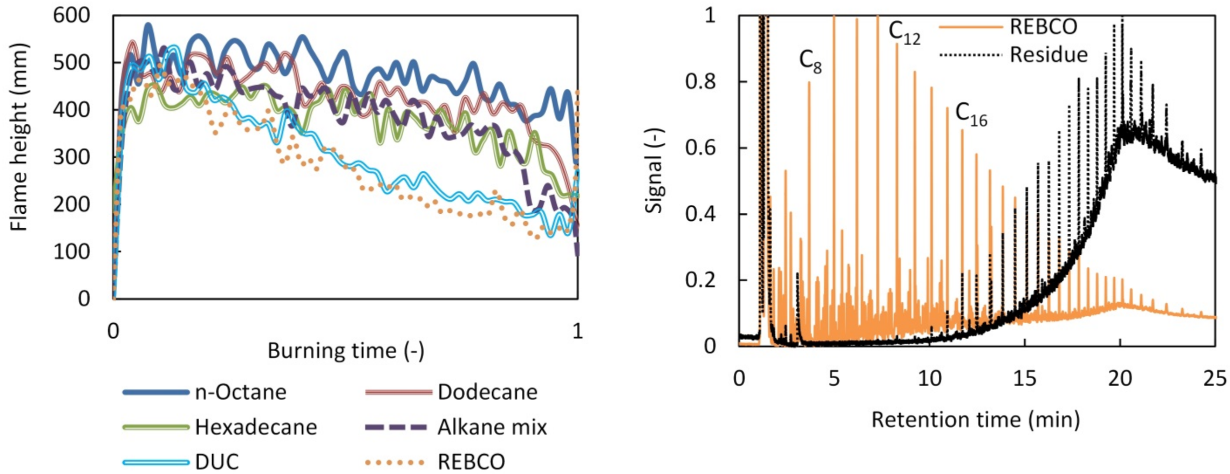

Figure 5. Flame height as a function of the burning time of various oils in the COFA (left) and the gas chromatograms of fresh REBCO and a typical REBCO residue (right).

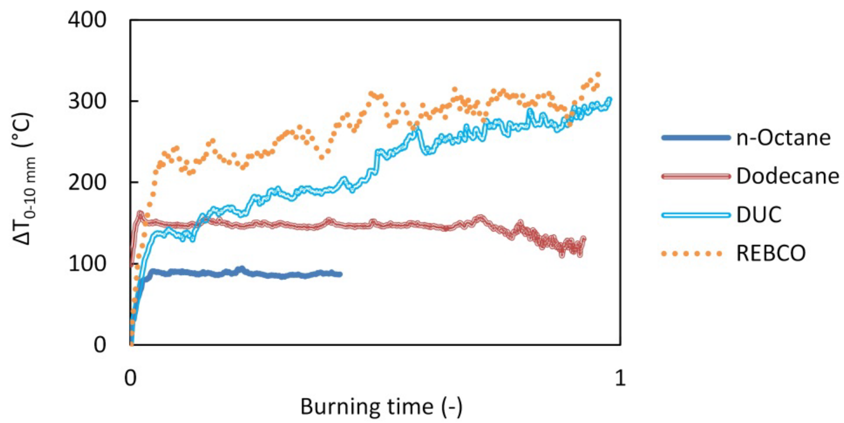

Figure 6. Temperature difference between the fuel surface and the temperature 10 mm below the fuel surface (initial oil-water interface) for fuels in the COFA with an initial slick thickness of 10 mm as a function of the burning time. The data shown is up to the moment when the thermocouple placed at the fuel surface no longer measured the surface temperature. The temperature gradients were representative for the temperature gradients in the fuels between all measured locations below the fuel surface (2, 3, 5 and 10 mm).

The above described phenomenon is clearly visible in the burning efficiencies in Figure 4, where the oils with the least volatile components have the lowest burning efficiencies. Although crude oils contain heavier components than diesel and have higher densities, they also contain a more substantial light fraction, as indicated by their lower flashpoints (Table 1). Crude oil burning efficiencies were therefore higher because they are an average value of the high burning efficiencies of their light components and the low burning efficiencies of their heavy components. Overall, the results show that the low burning efficiencies for multicomponent oils are due to an energy balance problem. With insufficient heat available to sustain the burning of the heaviest components in crude oils, in theory increasing the heat feedback (re-radiation and convection) to the fuel surface should increase the burning efficiency. These aspects are addressed in Sections 3.3 and 3.4.

3.2 Initial Slick Thickness

The burning efficiency as a function of initial slick thickness is shown in Figure 7. For both alkanes, the burning efficiency reached up to 99%, leaving only a very thin colored oil sheen behind. The slightly lower burning efficiencies (93-98%) for thinner alkane slicks (3-10 mm) were attributed to heat losses to the underlying water layer. For these very volatile oils, the heat losses start to dominate the energy balance at very thin thicknesses (see also Brzustowski and Twardus (1982)). Such thin thicknesses are reached (relatively) earlier for lower initial slick thicknesses so that relatively less oil is burned, thus resulting in lower burning efficiencies.

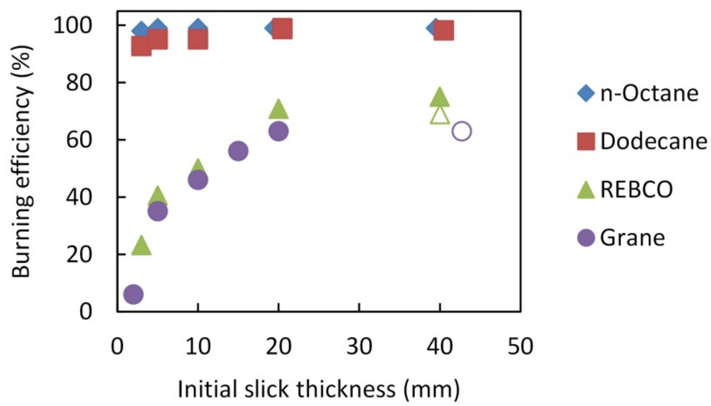

Figure 7. Burning efficiency as a function of initial slick thickness for oils tested in the COFA. The open symbols represent crude oil experiments without boilover. The Grane data was adapted from (Brogaard et al., 2014).

For the crude oils, the burning efficiency increased with increasing initial slick thickness from 23% to 75% for REBCO and from 6% to 63% for Grane. The very low burning efficiencies for thin crude oil slicks (2-5 mm) are most likely caused by the fast occurrence of boilover after ignition, which extinguished the fire after a short period of intense burning. The boilover phenomenon describes the explosive burning of crude oil, with increased burning rate and flame height for a short period (Evans et al., 1988; Garo et al., 1994; Guénette et al., 1994), typically caused by superheating of the water below the oil (Blander and Katz, 1975). During boilover, oil droplets were ejected outside of the Pyrex cylinder that contained the oil, with typically 50-80% of the total residue ending up on the water surface outside the initial oil pool. The time to boilover as a function of the initial slick thickness showed a good repeatability for each crude oil, which indicates that boilover did not randomly affect the burning efficiency. It is thus expected that the relative burning efficiencies among the different oil types as shown in Figure 4 and Figure 7 were not significantly affected by boilovers. For further discussion on the boilover phenomenon in small scale laboratory experiments (including the ice cavity and cone calorimeter setups), see Van Gelderen (2017).

At initial slick thicknesses of 20 mm and higher, the results in Figure 7 suggest that the heat losses no longer further influence the burning efficiency. The oil functions as an insulating layer between the burning surface and the oil-water interface, so a thicker initial slick decreases the heat losses to the water. Thus, as the initial slick thickness increased, the heat losses to the water layer decreased up to a minimum value, at which point the burning efficiency reached a maximum constant value.

Figure 7 clearly shows that the crude oils do not reach a burning efficiency of 90-99%. In fact, a minimum residue formation of about 30 wt% was observed for the 20 and 40 mm REBCO experiments. Considering that the obtained residues never sank and thus have a density < 1.00 g/ml, the residues inside the cylinder were estimated to have a thickness of 3.5 mm and 6.5 mm, respectively. Previous studies have described a "rule of thumb" regarding residue formation that states that for an initial slick thickness of ≤ 40 mm, a residue thickness of about 1 mm is formed (Buist et al., 1999; Buist et al., 2013). Based on this theory, a logarithmic increase would be expected for the burning efficiency as a function of the initial slick thickness with an asymptote close to a 100%. However, the data clearly show much lower burning efficiencies. While a burning efficiency of 90% would be expected for a 10 mm slick based on this rule of thumb, the observed burning efficiencies did not reach over 50%. The clear asymptotic function of the initial slick thickness in Figure 7 shows that the burning efficiency is not expected to reach above 80%, even for much higher slick thicknesses. These results thus provide another clear example of the limited burning efficiencies for crude oils on water in small scale experiments. From these results it becomes also clear that the initial slick thickness only has a limited influence on the maximum achievable burning efficiency.

3.3 Pool Diameter

The burning efficiency of ANS with an initial slick thickness of 10 mm as a function of the ice cavity diameter and as a function of the initial slick thickness in the smallest ice cavity is shown in Figure 8. The results clearly show that the burning efficiency increased with increasing pool diameter. Because the ice cavity experiments were conducted under very similar conditions, these results provide strong evidence that the burning efficiency is a function of the diameter. The results are also correspond well with other *in-situ* burning studies conducted at multiple scales (e.g. Bullock et al. (2017); Shi et al. (2016)). As expected, the burning efficiency showed a similar logarithmic function with respect to the initial slick thickness as in the COFA experiments (Figure 7). This indicates that the burning of oil in ice cavities is not fundamentally different from burning oil on open water. The observed trend of an increasing burning efficiency with increasing diameter can thus be considered to be representative of the results obtained in the other experimental setups. The influence of the ullage height and initial underlying water layer on the burning efficiency was not found to be relevant to this study and is therefore not further discussed herein.

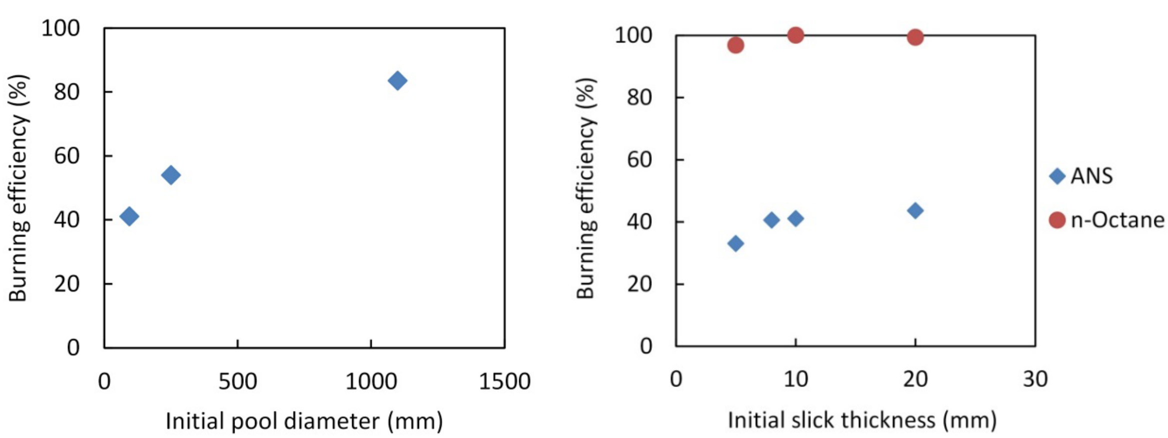

Figure 8. Burning efficiency of ANS with an initial slick thickness of 10 mm as a function of the ice cavity diameter (left) and as a function of the initial slick thickness for a pool diameter of 100 mm (right).

The increasing burning efficiency for larger pool diameters could be explained as a consequence of the increased burning rate per unit area with increasing pool diameter (*D*) for pool fires with $0.10 \leq D \geq 2.0$ m (Blinov and Khudiakov, 1957; Hottel, 1958). This correlation was also observed in the ice cavity experiments, which had burning rates of 12, 15 and 38 g/(s·m^2) for initial pool diameters of 0.1, 0.25 and 1.1 m, respectively. Following Eq. (2), a higher burning rate per unit area increases the heat release rate, which subsequently increases the heat feedback to the fuel surface. In this equation, $\dot{Q}_s$ is the heat feedback to the fuel surface (kW), χ_s is the heat feedback fraction, assumed to be 0.011 for hydrocarbons (based on Hamins et al. (1994)), $\dot{Q}$ is the heat release rate (kW), A is the area of the pool fire (m), $\dot{m}"$ is the burning rate per unit area (g/m^{2}s), χ_c a factor to accommodate for incomplete combustion (typically 0.7 for hydrocarbons) and ΔH_c is the heat of combustion of the fuel, which is 44 kJ/g for a typical crude oil.

$$\dot{Q}_s = \chi_s \cdot \dot{Q} = \chi_s \cdot A \cdot \dot{m}" \cdot \chi_c \cdot \Delta H_c \tag{2}$$

As discussed in Section 3.1, a higher heat feedback to the fuel surface would enable a crude oil to burn more of its components before heat losses to the water start to dominate the energy balance and extinguish the fire. A more detailed discussion on the energy balance for crude oil pool fires as a function of the pool diameter can be found in Van Gelderen et al. (2017a). The proposed theory of a higher heat feedback to the fuel surface leading to a higher burning efficiency was tested in the cone setup (Figure 2), of which the results are discussed in the next section.

3.4 Weathering and Heat Flux

The burning efficiency of weathered and fresh oils as a function of the incident heat flux (Figure 2) is shown in Figure 9. For all the tested oils, the burning efficiency generally increased with increasing incident heat flux. The burning efficiency results show that the evaporative weathering state of crude oil and a lack of volatile components (IFO 180) mostly reduce the burning efficiency at low incident heat fluxes (≤ 10 kW/m^2). Emulsification, on the other hand, clearly lowered the burning efficiency compared to the other oils. These lower burning efficiencies are, however, partially caused by the acquisition method of the residue mass. Theoretically, the water mass should not be included in Eq. (1) because water cannot be burned. In practice, some of the water evaporates prior to ignition, due to the imposed incident heat flux, or is ejected during boilover alongside ejected oil droplets and the initial water mass can therefore not be subtracted from the weighed residue mass. Because the oil and water in the residue could not be separated, the residue is thus not purely an oil residue, but an oiled water fraction residue. The actual burning efficiency of the oil fraction lies closer to the burning efficiency of the other unemulsified oils. Overall, the data show that at higher heat fluxes to the fuel surface, which are expected for large scale fires, the weathering state and oil type have only a limited influence on the burning efficiency. This result is supported by the high burning efficiencies that have been observed for evaporated and emulsified oil in large scale experiments and full scale *in-situ* burning operations (Allen, 1990; Guénette et al., 1995; Guénette and Wighus, 1996).

The high burning efficiencies for Grane at incident heat fluxes of 0 and 5 kW/m^2 are possibly caused by a more vigorous boilover phase than at higher incident heat fluxes, as seen from the heat release rate data (Van Gelderen, 2017; Van Gelderen et al., 2017b). Despite the absence of contact with the water layer, burning the Grane in the cone calorimeter setup resulted in a mild boilover phase. These boilovers were attributed to superheating of the light components inside the slick as they were trapped by the heavy components. A full discussion on this topic is outside the scope of this paper (for more information see Van Gelderen (2017)). Because the burning efficiency results of Grane overall increased with increasing incident heat flux and the general trend matched the results of the other oils, this topic was not studied further.

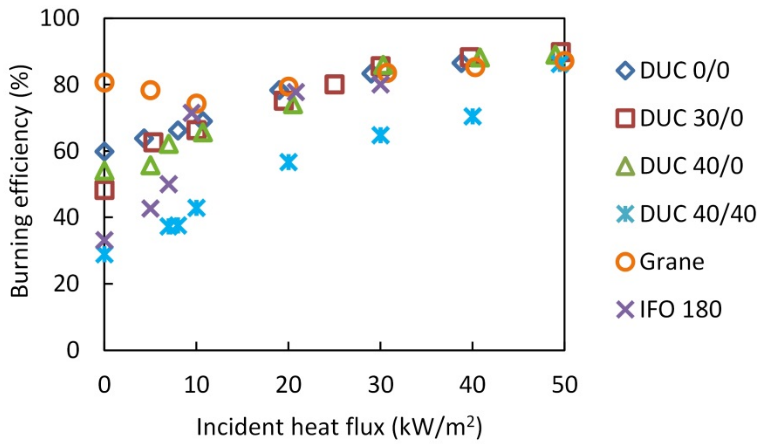

Figure 9. Burning efficiency as a function of the incident heat flux for oils tested under the cone calorimeter. Data points are jittered on the x-axis for clarity reasons.

The increasing burning efficiencies for increasing incident heat fluxes correspond well with the postulated theory that a higher heat feedback to the fuel surface reduces the influence of heat losses to the water and thus increases the burning efficiency. None of the oils in Figure 9, however, reached burning efficiencies of 90-99% that have typically been observed in large scale crude oil fires on water (Allen, 1990; Brandvik et al., 2010; Guénette and Wighus, 1996; Potter, 2010). An estimate of the heat feedback to the fuel surface for a 10 m diameter pool fire was calculated using Eq. (2) to determine whether the tested incident heat fluxes are representative of large scale pool fires. According to Buist et al. (2013), the regression rate of a large, unemulsified oil fire on water is 3.5 mm/min. This translates to a burning rate of 3.9 kg/s for a 10 m diameter pool fire of a crude oil with a density of 0.85 g/ml. The heat feedback to the fuel surface for such a crude oil fire on water would then be approximately 17 kW/m^2.

Experimental results of heat feedback measurements to the fuel surface in JP8 pool fires with a diameter of 20 m, however, showed radiative heat fluxes with peaks up to 100 kW/m^2 (Gritzo et al., 1996). The measured regression rates of these JP8 pool fires were only slightly higher, 4.0-4.9 mm/min, than the regression rate reported by Buist et al. (2013). This regression rate difference cannot explain the much higher estimated averaged heat feedback over the full fuel surface of about 40-60 kW/m^2 in the JP8 fires compared to the calculated 17 kW/m^2 for a large crude oil fire. As such, it is likely that the calculated 17 kW/m^2 for the heat feedback to the fuel surface for a large scale crude oil fire is underestimated, most likely caused by uncertainties in the χ_s value. Based on the experimental results from Gritzo et al. (1996) and the reported regression rate for crude oil from Buist et al. (2013), a more realistic heat feedback range for large scale crude oil fires therefore seems to be 30-60 kW/m^2.

For an incident heat flux of 30-50 kW/m^2, the burning efficiency for the tested oils varied between 65-89% and seems to reach a maximum value at an incident heat flux 50 kW/m^2 (Figure

9). Extrapolating the trends observed in Figure 9 to higher incident heat fluxes suggests that burning efficiencies of > 90% are unlikely for the conducted type of experiments. The results thus suggest that the high burning efficiencies observed for large scale crude oil fires on water are not only caused by the increased heat feedback to the fuel surface compared to small scales. It is, however, unlikely that the burning efficiency deficit of Figure 9 compared to large scale fires could be explained as a function of the initial slick thickness. Because the relative heat feedback to the fuel surface is larger for large scale fires than for small scale fires (Section 3.3), less insulation from the thickness of the slick should be needed to sustain the fire. It is therefore reasonable to expect that the maximum burning efficiency for large scale fires can be obtained for initial slick thicknesses lower than the thickness of 20 mm found in this study (Figure 7). The influence of the initial slick thickness should thus be an inversed function of the pool diameter and the effect of the initial slick thickness on the burning efficiency for operational scale fires may become near negligible.

One possible additional factor that could contribute to the high burning efficiencies in large scale fires is the wind induced herding of surrounding oil into the fire (Allen et al., 2011; EPPR, 2015). The buoyancy controlled rise of a hot smoke plume from a pool fire causes entrained flows of air into the fire and the plume (Heskestad, 2016), and such air flows become stronger with increasing pool diameter. During the *in-situ* burning operations that were part of the response to the Macondo spill, it was observed that oil on the sea surface around the fire was herded into the fire by these entrained flows into the fire (Allen et al., 2011). By feeding oil to the fire, the oil slick thickness increases which counteracts the reduction of the slick thickness, as oil is consumed by the fire. More oil can then be burned before the heat losses to the water dominate the energy balance (Section 3.1), and the fire is extinguished. As such, the herding of oil into the fire increases the burning efficiency. This oil herding phenomenon, induced by entrained flows, could therefore possibly contribute to the high burning efficiencies observed for large scale crude oil fires on water.

Currently, there is only very limited experimental data available on the differences between the fire dynamics of small and large scale crude oil fires on water. There is therefore no reason to assume that the two factors discussed above (increased heat feedback and herding of oil into the fire) are the only two factors that increase the burning efficiency for large scale crude oil fires on water compared to smaller scales. Further studies should be conducted that focus on the fire dynamics of large scale crude oil fires on water to accurately determine the driving factors behind the very high burning efficiencies observed for such operations.

Overall, the results of this study suggest that the high burning efficiencies obtained for large scale *in-situ* burning operations are inherent to the size of the fire. This is partially due to the vaporization order of crude oils, that require a continues increase of energy to evaporate all of its components, and increasing heat losses to the water as the oil slick heats up over time. Other parameters, such as the initial slick thickness and the weathering state of the oil could not be used to explain the burning efficiency difference between small and large scales. Although the heat feedback to the fuel surface stabilizes for pool fires with diameters above 1-2 m, at this point the burning efficiency has typically already reached maximum values of 90-99%. In this range of diameters, from small scale to 1-2 m, the pool diameter has the most controlling effect on the burning efficiency before it reaches its maximum value. The pool diameter is thus the key controlling parameter that determines the burning efficiency of *in-situ* burning of crude oil on water. Once a large oil slick has been ignited, it is as such expected to result in high burning efficiencies, independent of other the properties of the oil or environmental conditions.

4 Conclusion

The burning efficiencies of pure oils, refined oils, crude oils and weathered crude oils were studied on water, in ice cavities and in a cooled sample holder subjected to an incident heat flux. In small scale experiments on water, the burning efficiency decreased from 99% to 20% with decreasing amount of volatile components and increasing amount of non-volatile components in the oil composition. This dependency of the oil composition in small scale experiments was attributed to the volatility controlled vaporization order of multicomponent fuels and increasing heat losses to the water layer over time. Based on this, it is postulated that in small scale pool fires, contrary to large scale fires, the heat feedback to the fuel surface is insufficient to cancel out these heat losses, resulting in the premature extinction of the fire.

By increasing the initial slick thickness, the burning efficiency increased up to a maximum value around an initial slick thickness of 20 mm. These maximum burning efficiencies were limited to 63-75%, which indicated that the initial slick thickness only has a limited influence on the burning efficiency. Scaled experiments in ice cavities clearly showed that the burning efficiency increases with increasing pool diameter under otherwise similar testing conditions. These results confirm that the burning efficiency is a function of the pool diameter for crude oils burning on water. This correlation was attributed to the increased heat feedback to the fuel surface in large scale fires that could cancel out the heat losses and provide sufficient energy to evaporate the heaviest components in crude oil. Burning efficiencies indeed increased with increasing incident heat flux for fresh and weathered oils, as expected. Weathering of crude oil was shown to have only a limited effect on the burning efficiency at incident heat fluxes that were equal to or greater than 20 kW/m^2. The results thus indicate that the pool diameter is the one parameter that to a great extent controls the burning efficiency.

The influence of the pool diameter could, however, not solely be attributed to an increase in the heat feedback to the fuel surface. The burning efficiencies observed in large scale *in-situ* burning experiments (≥ 90%) were not reached for the conducted small scale experiments. At incident heat fluxes of 40-50 kW/m^2, which correspond well with measured heat feedback values in large scale JP8 pool fires, the burning efficiency did not reach above 86-90%. The high burning efficiencies observed in large scale crude oil fires on water are therefore probably caused by a combination of multiple factors associated with a large pool fire diameter, and this merits further studies at different scales.

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